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LLNL-TR-665139

Report on High-Contrast Advanced Radiographic Capability Review

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December 5, 2014

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Report on High-Contrast Advanced Radiographic Capability Review

October 31, 2014

Chair:

Alan S. Wan, Lawrence Livermore National Laboratory

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Jake Bromage, Laboratory for Laser Energetics, University of Rochester

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Introduction:

System description and applications

The Advanced Radiographic Capability (ARC) project at the National Ignition Facility (NIF) is designed to generate picosecond duration, kilo-Joule laser pulses to produce x-rays for backlighting NIF experiments. The baseline concept (Figure 1), utilizing a single NIF beam quad, diverts the beamline(s) using insertable pick-off mirrors to a compressor chamber in the target bay and focuses it to target chamber center. When fully implemented, ARC will use a quad of NIF beamlines to deliver eight Petawatt-class, high-intensity pulses in a split aperture configuration (2 short pulse apertures per NIF beamline). These short pulses will be adjustable in energy (up to 13.2 kJ in full implementation), delays (0-80 ns) and pulse durations (1-50 ps) and can be individually pointed to targets. ARC will enable dynamic, multi-frame x-ray imaging (radiography) on NIF for applications in laser driven fusion and other high-energy density science missions. The near-term missions in support of the SSP program are described below.

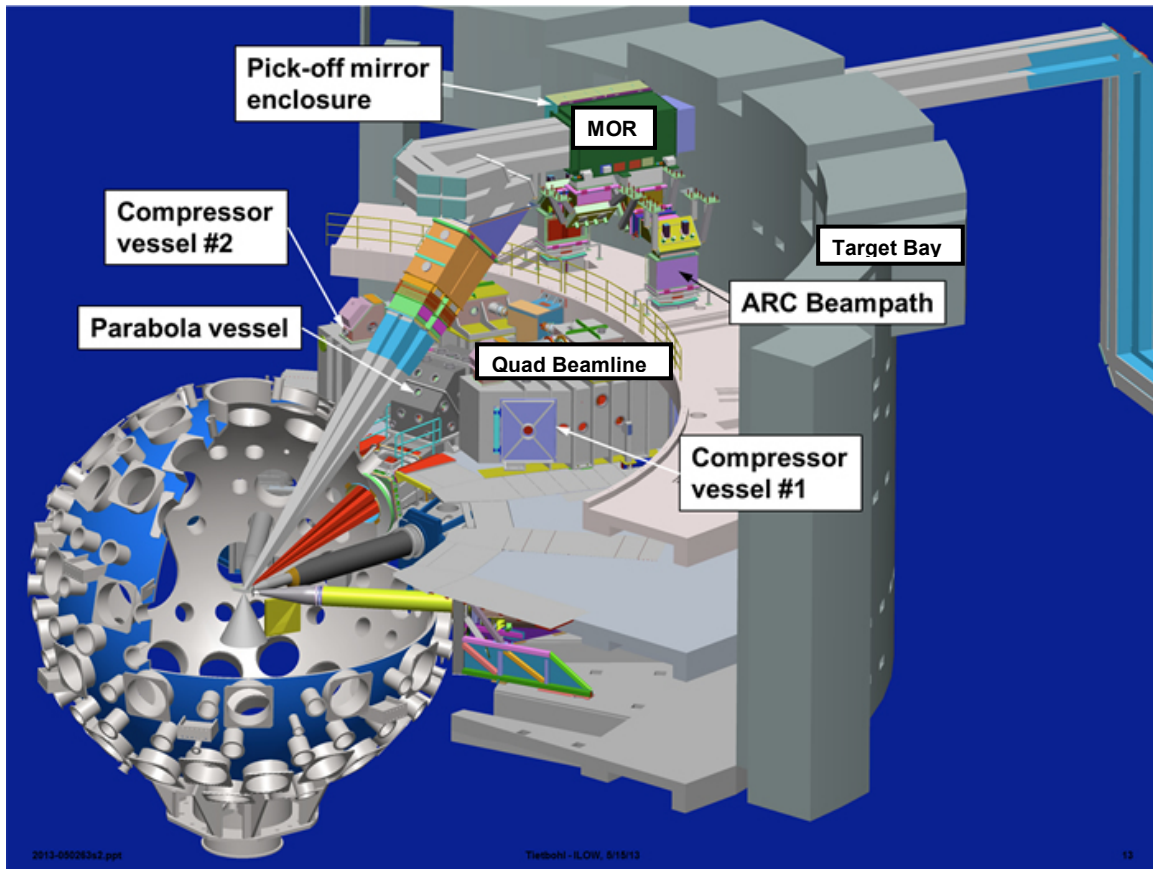


Figure 1. ARC baseline concept on NIF

Compton Radiography of compressed DT fuel - Time dependent asymmetries will drive shape and areal density non-uniformities on the imploding DT fuel, degrading

compression and leading to incomplete conversion of kinetic energy to heating, impairing ignition. X-ray radiography of the imploded fuel configuration is hence highly desirable. To avoid being swamped by the core self-emission, we need to operate at > 75 keV photon energy. ARC will provide the required conversion efficiency at $10\text{-}20\text{ }\mu\text{m}$, 30 ps resolution. The current program plan requires data generated using this capability by the end of FY15 in support of the “path forward” plan.

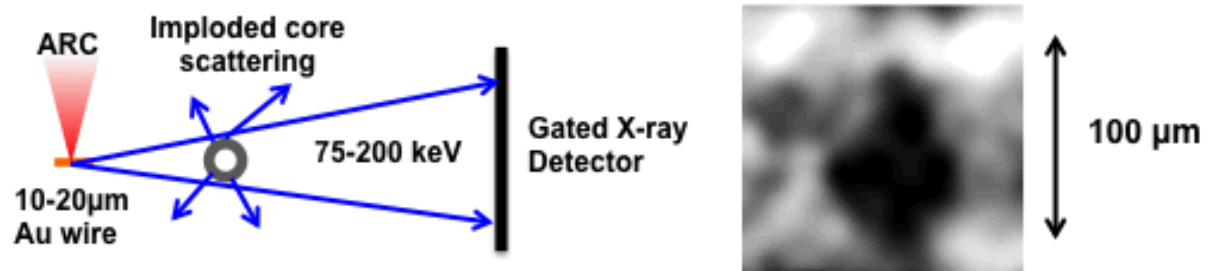


Figure 2. Compton Radiography

High-Z Strength - Understanding material properties under extreme conditions will provide critical constraints for and validation of codes, constitutive models, and inter-atomic potentials of importance to many LLNL programs. ARC will provide the 20-80 keV radiographic x-rays needed to infer the strength of high Z materials of interest by measuring the hydro-instability growth rates of 1D pre-imposed ripples. The Stockpile Stewardship customer for this capability requested data by the end of FY15.



Figure 3. High-Z Strength

Complex Hydrodynamics - Understanding the evolution of complex hydrodynamics and the interplay with drive asymmetry on mid-Z imploding shells is important to LLNL programs. ARC point sources can provide the 2D radiography at 20-40 keV over the required large 1.5 mm field-of-view. SSP data with this capability has been requested for mid-FY15 and is on the critical path for the ARC project.

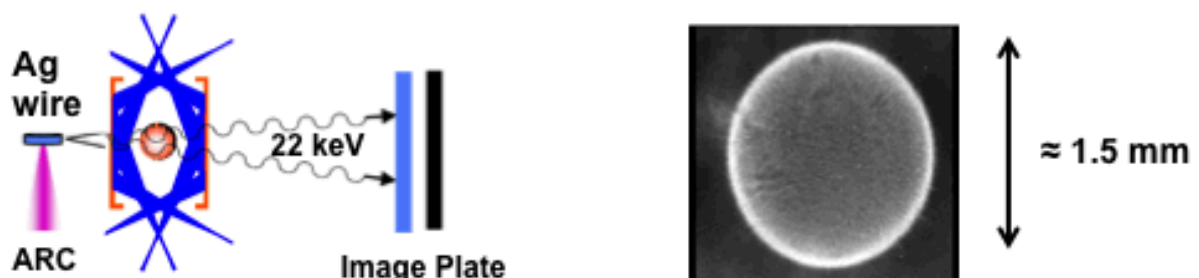


Figure 4. Complex Hydrodynamics

Charter:

Recent discoveries predict Advanced Radiographic Capability's (ARC) non-compliance with pre-pulse project completion criteria in accordance with program requirements.

This committee is chartered to review the issues and its proposed solution and deliver a critical independent assessment, focusing on the requirements and conceptual design for a replacement high-contrast ARC front end.

The committee is charged to answer the following questions:

1. Are the pre-pulse requirements for the ARC well understood and appropriate?
2. Is there sufficient evidence to show that the predicted pre-pulse problem with the current design is real?
3. Is the proposed solution technically sound and low risk?
4. Is the plan and schedule for implementation credible?
5. Is the plan for mitigating other outstanding project risk adequate?

Executive Summary:

The High-Contrast Advanced Radiographic Capability Review took place at Livermore On October 30-31, 2014. Detailed agenda is listed in Appendix A of this report. The committee is grateful to all the briefers who did an excellent job in presenting the issues, evidences, and proposed solutions and plan. The tour of the facility gave the committee insight on both the magnitude and challenges of the tasks. The committee was very impressed with the technical qualification of the ARC team as well as their professionalism and openness. The committee would also like to thank the administrative team, including Trina Voelker, Tara Chavez, Stephanie Loreda, Carly Limtiaco, Nyla Wlodarczyk, for their preparation and support.

As a high-level summary, the committee finds that the ARC Project has assembled a well-qualified team to deliver a technically sound solution to meet the defined programmatic requirements. There are no show-stoppers that we can identify to prevent the team from delivering a high-contrast front end system in the FY2015 time frame, representing a delay of 6-9 months from the original plan in delivering the capability to the users for programmatic applications.

There are some high-level recommendations by the review team, listed below but expanded in more details in the later sections:

- Tighten up the pre-pulse specifications to cover the entire temporal region of interest to experimenters
- Complete the FMEA on the front end as early as feasible to identify any other risks that might need attention/mitigation
- Complete the detailed project schedule and plan and generate some schedule float
- Get early data on the most important technical risk areas as early as possible
- Continue to use the risk management process presented to track remaining ARC system risks in parallel with team focus on the front end pre-pulse issue (don't lose sight of the rest of the project).

The detailed report is constructed to directly respond to each one of the five questions in the tasking, including summary of the presentation, and comments and recommendations of the committee.

Question 1: Are the pre-pulse requirements for the ARC well understood and appropriate?

Finding:

- The two pre-existing pre-pulse threshold requirements on target, $< 10 \text{ J/cm}^2$ up to -1 ns before peak power and $< 1 \times 10^{12} \text{ W/cm}^2$ up to -200 ps before peak power are still valid (and may be conservative) to maintain the relevant ($< 300 \text{ keV}$) x-ray conversion efficiency and required small source size demonstrated at OMEGA EP and the Titan facility.
- The current expression of the pre-pulse requirement does not completely describe the temporal region of interest

Comments:

The first requirement is bolstered by experiments at the Titan facility showing a drop in relevant x-ray conversion efficiency and increase in unwanted MeV conversion efficiency as pre-pulse energy intentionally increased. This is attributed to the calculated increased 1D expansion speed of the 1ω critical density surface that scales close to the theoretical direct-drive limit, $\sim (\text{intensity } I)^{1/3}$. Hence the current $5\text{-}10 \text{ kJ/cm}^2$ ARC pre-pulse, which leads to a calculated $100\text{-}\mu\text{m}$ critical surface expansion has to be reduced by a factor of 1000 back to 10 J/cm^2 to keep the expansion down to $10 \mu\text{m}$, the original width of the thinnest targets envisaged.

The first pre-pulse requirement is somewhere between appropriate and conservative, as based on conservative 1D expansion simulations presented. The second requirement meshes well with first requirement based on limiting the critical surface expansion as the main metric. Details:

Originally, the $<10 \text{ J/cm}^2$ requirement up to 1 ns before the main pulse was based on avoiding distortion of the target (and hence change in the solid target source size) due to a shock launched by an early pre-pulse at the $\mu\text{m/ns}$ level. The new information on pre-pulse-modulated conversion efficiency and plasma expansion (from Jarrott 2014) that was presented is very timely as it provides more physics underpinning the requirements. However, there is a large difference in the 1D ARC simulation results and the HYDRA Titan simulations from the Jarrott 2014 paper. Specifically, the 5000 mJ Titan point (that leads to $27 \mu\text{m}$ expansion) is focused to a $50 \mu\text{m}$ spot so corresponds to 300 kJ/cm^2 . This is compared to the ARC 1D calculation at 0.1 kJ/cm^2 predicting a similar expansion at 3000x less fluence. Is this because the ARC simulation includes the expansion from the higher intensity pre-pulse epoch occurring earlier than -1 ns? The fact that the minimum Titan ns pre-pulse level of 1 kJ/cm^2 provides acceptable conversion efficiencies and low enough expansions per simulations suggests the first requirement may be conservative.

The plasma expansion argument can be generalized if we postulate that the main metric is keeping the critical density expansion (call it L) no greater than the initial source size by the following approximate equation:

$$L \sim \int I^{1/3} dt$$

This suggests that 10 J/cm^2 delivered over say 1 ns ($= 10^{10} \text{ W/cm}^2$) and arriving 1 ns early will provide same expansion as a 10^{13} W/cm^2 pre-pulse arriving 100 ps early, or a 10^{12} W/cm^2 pre-pulse arriving 215 ps early, very close to the existing second requirement. That is the reason for saying the two requirements appear self-consistent.

A final smaller point is that the requirements are presented per beamlet, but the experiments will overlap 2 or 4 beamlets, so bit less margin than is shown, but within uncertainties given the slow $I^{1/3}$ scaling.

Recommendations:

- Tighten up the pre-pulse specifications to cover the entire temporal region of interest to experimenters
- The two hydrodynamic simulation results should be reconciled by bounding the problem comparing 1D planar expansion to a more realistic 1D spherical expansion
- An intensity vs time envelope spec should also be considered based on the critical surface expansion model, which would most naturally be of the form $I \sim 1/t^3$ that already fits the two existing requirements and the approximate form of the pre-pulse. That would clarify the reasons for the existing requirements and avoid a fluence requirement that may be overly conservative if delivered over such a long time that the intensity is insufficient to melt the target.

Question 2: Is there sufficient evidence to show that the predicted pre-pulse problem with the current design is real?

Finding:

- The design team has demonstrated that the ASE concerns are real and are of a major concern.
- The discussions showed that there are gaps in the pre-pulse specifications and should be revisited (see discussion on requirements, above).
- There is a concern that there may be other pre-pulse sources that are being masked from the current baseline measurements.

Comments:

- Clearly the ASE from the oscillator compounded by the B^2 effect from subsequent amplifiers is the dominant source of pre-pulse in the system and must be eliminated. It is not entirely clear whether other lower level pre-pulses may exist and become apparent when the ASE source is gone. Potential pre-pulses at T-5ns and T-1ns detected in photodiode measurements need to be investigated further.
- The review team introduced a one-dimensional model that showed a plot of Time in picoseconds vs. Fluence (J/cm^2) that covered a span of 6 decades. The plot articulates the various regions of the pulse evolution. Two regions were identified that are associated with Amplified Spontaneous Emission (ASE) as the region to crease the contrast of the ARC pulse. The plot shows the (ASE) floor and ASE pedestal are the areas that show higher than desired fluences between $t < -1$ ns and $t < -200$ ps associated with the ARC pulse evolution. It was shown that the past NIF ARC models did not correctly account for the B-dependent growth ($\sim B^2$) of the ASE that is responsible for the “pedestal” in the pulse shape. When this pulse pedestal gets amplified and then compressed, the pre-pulse equates to a fluence increase of (~ 20 dB) in the base of the final pulse and is spread in time. This temporal spread in energy was shown to interfere with the physics experiments that cannot tolerate energy (at the higher levels) on the target prior to the main pulse. (See references in M. Hermann’s presentation pp 4-5).

Recommendations:

- Complete a Cross-correlator scan of the regenerative amplifier output as soon as possible with the goal of determining any additional pre-pulse sources.
- Consider expanding the AFECT table to allow additional permanent diagnostic systems, including the Scanning Cross-correlator measurement.

Question 3: Is the proposed solution technically sound and low risk?

Finding:

- Sound concept with a highly qualified team
- Front-end modification is considered the only realistic way for ARC to reach compliance in the available time. Other approaches (e.g., frequency conversion, adding pinholes, target modification) have been rejected [see Hermann, slide 6]
- Only one solution was presented, and no others identified that meet the constraints of the NIF system.
- Three major upgrades are proposed to obtain a front-end contrast of 100 dB
 - Replace SESAM cleaner with OPA
 - Replace CFBG stretcher with bulk stretcher
 - Replace transport fibers by moving front end to above the PAM for 35T

Comments:

- Other pre-pulse mechanisms: There is sufficient evidence to show the pre-pulse problem is real. However, there was not an assessment of other sources of pre-pulses (e.g., stretcher/compressor optics, pre-pulses in the multi-pass amplifiers) that may dominate after the ASE is reduced and still cause non-compliance.
- Existing and new post-pulses: One must quantify the maximum tolerable level of post-pulse within the duration of the chirped main pulse for the current and future levels of B-integral. Changes in the front end may produce new post-pulses.
- Pump-signal timing at OPA: Timing using the vernier effect requires a small difference between the repetition rate of the oscillator and OPA-pump regen. Is this consistent with the option of using the MOR oscillator and then switching to a COTS device?
- Pre-pulse from SLM: Pre-pulse reflections from the SLM window (Boulder Nonlinear) are mitigated by programmatically adding tilt to the wavefront. This approach may need to change if the output fiber is removed to eliminate the B-integral contribution (~ 1 for 5-m of PZ fiber)
- Stretcher optics requirements: As there is currently no pre-pulse requirement for after -200 ps, there is no way to setting requirements for the mirror and grating of the new stretcher other than stating 'best effort'.
- Spectral shaping: The insertion loss of the Spectral Shaper is significant ($\sim 20\times$) and questions remain about the output format (fiber vs. free space). Reduction of this loss would allow one to relax energy/loss requirements of other elements. The bulk stretcher offers an opportunity for adding apodization and possibly phase shaping at the Fourier plane. Since the OPA output energy depends nonlinearly on the seed energy, there might be an efficiency benefit in moving the Spectral Shaper before the OPA seed.
- Alignment budget for stretcher: Analysis of the alignment budget for the stretcher was not presented, particularly in terms of residual chromatic aberrations (angular dispersion, etc.).

- Fiber delivery to DRT for mode cleaning: One concern is spectral aberrations causing instabilities after the beam is injected into the DRT. Can a short length of PZ fiber be used as a mode filter without incurring too much B-integral (only 50 nJ)?

Recommendations:

- Develop the plan and layout for adding a third-order cross correlator to the AFECT.
- If possible, add an inter-beamlet scanning cross correlator to the ADT so that pre-pulses from the MPA, main beamline and compressor can be quantified at times shorter than can be measured using the diodes and/or evaluate the possibility of using a single-beam commercial cross-correlator at that location.
- Develop a plan for measuring pre- and post-pulses in the beamline (e.g., from pencil beams and reflections in multi-pass amplifiers) after the DRT using existing front end in current ARC configuration.
- State a requirement for post-pulses in the front end, derived from the pre-pulse requirements, for the expected levels of B-integral throughout the stretched-pulse section of the system
- Present a more explicit insertion loss budget between the OPA and DRT to understand the risk of under-seeding the regens (current design point is 50 nJ). Assess via system model and simulations if the Spectral Shaper or other components currently located between the OPA and DRT could be moved before the OPA.
- The pulse energies expected from the regen and OPA are 1.5x and 2x higher than are currently used on OMEGA EP. Although it is not clear that the proposed values are unrealistic, this should be evaluated as early as possible, using prototype equipment if necessary, if the margins are tight.
- Investigate the risk from the stretcher optics of increasing the pre-pulse pedestal after -200 ps and derive appropriate requirements.
- Investigate 2-pass vs. 4-pass stretcher to eliminate residual angular dispersion ($1/15^{\text{th}}$ of beam divergence)
- Test whether installing a GLX-200 in 33T is mechanically sound as soon as possible to check whether this is a realistic option given available time.
- Need to define whether will use Au or MLD gratings in the bulk stretcher, taking into consideration the impact on temporal contrast.
- Assess possibility of improved spatial mode cleaning (if hasn't been done already) using short lengths of PZ fiber before the DRT.

Question 4: Is the plan and schedule for implementation credible?

Findings:

Project Resources

- Project organization and assigned resources appear to be well aligned with the scope of work, with the exception of integration and installation. Not including this scope in the same WBS and managing it as an integrated project introduces risk.

Project Schedule

- The schedule provided to the review committee was not detailed enough to determine if it is realistic for the scope identified. A detailed integrated schedule will help to identify float or ways to generate float.
- Schedule risk cannot be adequately assessed without an FMEA and risk matrix.

Fabrication and Procurements

- Model based manufacturing should work well for this project. Previous NIF experience with this approach provides some confidence that additional risk is not being introduced. The number of fabrications and procurements is likely to be high but the planned coordinator support is only half an FTE, which seems inadequate.

Comments:

- Co-locating the team was a good move
- The project manager and team have a lot of experience with complex NIF projects, so where information may be lacking in the review material, there is a level of confidence that many of the observed “possible issues” may have already been thought through and addressed
- There may be resources that are over-committed when multiple ARC activities are occurring at the same time. A way to view the front end project activities in the context of other ARC and facility activities that affect installation is needed.
- A budget was not discussed. It is assumed that the project is operating within an approved budget and that contingency is available to fund over-runs in manpower if needed to maintain schedule or mitigate technical risk.
- Too many hardware options can dilute resources and lead to delays in freezing the design and integrating.
- Plug-and-play proposal appears to be the only way for ARC development to continue on the main beamline during the front-end build. B381 allows integration testing and qualification (albeit in harsher environmental conditions) with unimpeded access.
- One month for NIF installation seems marginally adequate if everything goes well.
- Integration schedule (July 2015) will require high priority during this FM&R.

- Not clear whether the MOR front end will remain active up to and beyond the integration of the new front end, or whether parts will have to be cannibalized.

Recommendations:

- Develop a resource loaded schedule that includes activities from design through installation for the Front End Design and include other ARC and facility activities that may occur in parallel and affect assigned resources
- Include integration and installation WBS elements in the project
- Look for ways to build float into the schedule
- Complete the FMEA as soon as possible and include integration and installation activities to identify workarounds ahead of time
- Consider identifying a coordinator who is familiar with this process and increase the coordinator resource to 100% and evaluate if more is needed
- If enough parts are available to complete a prototype, integrated system, this should be done as soon as possible
- Down-select where multiple options exist ASAP. Parallel efforts should be maintained where there is significant technical or schedule risk.
- Identify additional shop resources to complete manufacturing of partially completed model-based-manufacturing items
- Include in the schedule the effort required to complete component machining and to precision clean the parts

Question 5: Is the plan for mitigating other outstanding project risk adequate?

Finding:

- Sound risk assessment methodology has been employed by the project. Risks in 15 functional subsystems were identified and assessed using standard FMEA systems engineering risk management practices. Mitigation actions defined by this process were prioritized based on the return on investment or leverage in the risk mitigation actions.
- Risk management is active and ongoing. Priorities shifted from Q1FY14 to Q1FY15 reflecting increasing priority of front end pre-pulse issue.
- Laser damage remains a top risk concern requiring continued attention.
- Radial chromaticity imparts a 90- μ m sweep on target. The two beamlets sweep linearly in opposite directions.
- Energy will be limited to 1.2 kJ per beamlet by damage of AG4 and AM8
Energy will be limited to <1.2 kJ per beamlet by damage of AM7 prior to new coating (due beginning of FY16)
- Two beamlets per target are required to reach an acceptable probability of producing the required x-ray flux

Comments:

- The committee was given a limited look at other outstanding risks. It may benefit the project to present a more comprehensive review.
- Due to sweep in a single plane, uncorrected radial chromaticity has the potential to limit imaging options to only one axis
- Short-pulse damage testing is valuable to verify current optics and qualify potential vendors
- Mid spatial frequencies from the gratings may affect both spatial and temporal contrast
- Vacuum vessel cleanliness seems to be well under control
Need to specify optic damage inspection process, as compared to normal procedure for NIF optics

Recommendations:

- Complete the FMEA on the front end as early as feasible to identify any other risks that might need attention/mitigation
 - Better physics definition for the entire time scale
 - System performance
 - Including model the new front end performance
- Get early data on the most important technical risk areas as early as possible
- Continue to use the risk management process presented to track remaining ARC system risks in parallel with team focus on the front end pre-pulse issue (don't lose sight of the rest of the project).

- Mitigation of SBS backscattering threats
 - Include diagnostics to quantify backscattering
 - Consider further quantification experiments
- Maintain in the design the option to correct for radial chromaticity
- Make the decision soon on oscillator vendor, and consider borrowing one for initial activation
- Specify the ARC optic damage inspection process, as compared to normal procedure for NIF optics

Appendix A: Agenda

Review of ARC Pre-Pulse and Front-End Design

October 30 - 31, 2014

Thursday, October 30, 2014

8:30 a.m.	Welcome, Charge to Committee
8:45	Executive Session
9:00	ARC Project Overview & Status
10:00	Baseline ARC Front-End Design & Performance
11:00	Tour of ARC (B581)
12:30 p.m.	Working Lunch
01:00	ARC Pre-Pulse Requirements & Options Down-Select
01:45	ARC High-Contrast Front-End Design & Physics Basis
02:45	Break
03:00	ARC High Contrast Front-End Project Plan
03:30	Discussion
04:00	Executive Session
05:00	Adjourn for the day

B481 R2005

D. Larson
Committee Only
P. Wegner
J. Heebner
G. Tietbohl

M. Hermann
J. Heebner

M. Bowers
All
Committee Only

Friday, October 31, 2014

8:30 a.m.	Executive Session (as needed)
10:00	Break
10:15	Executive Session (as needed)
11:30	Out-Brief
12:00 p.m.	Adjourn

B481 R2005

Committee Only

Committee Only
By Invitation

Host: Alan Wan

Administrative Contact: Trina Voelker, Tara Chavez

Clearance: Unclassified